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APPLICATION OF BAYESIAN NETWORKS TO ESTIMATE THE PROBABILITY OF A TRANSFER AT A PUBLIC TRANSPORT STOP

Summary. *Optimizing transfers during public transport operations is one of the essential components of improving the quality of transport. Several factors influence the passenger's perception of a transfer: from the personal characteristics of the user of transport services to the parameters of the route network, trip characteristics and the design of transfer stops. The method of constructing Bayesian networks was used as one of the effective methods for solving problems of forecasting complex systems to find the relationship between different types of input data that affect the probability of making a transfer at a stop.*

The need for a transfer arises for a passenger when two reasons are combined: the need to make a trip between two transport areas and the lack of a direct public transport route between these transport areas. The number of needs for trip will depend on the number of residents in the departure zone, and the probability of not having a direct route will depend on the total number of routes departing from this zone. A simulation was carried out in the PTV Visum software environment (on the example of Lviv city) to determine the impact of these factors on the probability of changing at a stop. As a result, data were obtained on the total amount of passenger exchange at the stops of the public transportation system with distribution into the number of passengers disembarking at the stop, the number of passengers transferring at this stop, and the number of passengers going (up to 200 m) to another stop to transfer. The average waiting time for a transfer at a stop depends on both the number of routes passing through the stop and the regularity of traffic. Strict adherence to traffic schedules helps to reduce the average waiting time for a transfer. A comparison of the results of calculating the probability of a transfer at one of the stops using calculations based on field observation data and using modeling was carried out to check the adequacy of the modeling. The calculated probability is 0.16, the simulated probability is 0.12.

Key words: *route network, Bayesian network, transport modeling, probability of transfer, PTV Visum.*

1. INTRODUCTION

The demand for services in complex transport and logistics systems, which include the urban passenger transport system, is characterized by the uncertainty associated with incomplete or unclear information about the functioning of individual elements of the system and the influence of the human factor. Therefore, it is advisable to apply system analysis and decision-making theory methods to solve problems related to forecasting or optimization of such systems.

Bayesian networks with hidden variables are one of the highly effective methods of a systematic approach to solving weakly structured problems. They allow, based on incomplete data, to find cause-and-effect relationships between parameters and to obtain an adequate probabilistic predictive model at the output [1].

Bayesian networks represent a system of probabilistic processes in the form of a graph, where vertices represent random variables, and edges represent the presence of connections between vertices (that is, the influence of one variable on another). Each network vertex is assigned a table of conditional or unconditional (for independent variables) probabilities [2]. The advantages of applying Bayesian networks are the possibility of using different types of input data (statistical information and expert assessments) and different types of variables (discrete or continuous).

2. PROBLEM STATEMENT

When forecasting the demand for transportation in the urban transport system, one of the problems is taking into account the probability of a passenger transfers at an urban public transport stop. The transfer is one of the elements of the structure of the time costs of the trip (along with the duration of the trip, the time of approach to the stop, and the waiting time). These costs characterize the level of transport accessibility as one of the main quality criteria of the urban transport environment.

Accessibility standards depend on the size of the settlement and are regulated in Ukraine by State Building Regulations V.2.2-12:2018 "Planning and Development of Urban Territories". For cities with a population of more than 800,000 people, the standard travel time is 45 minutes. The development of the urban route network, its density, the saturation of routes with vehicles, and the regularity of traffic are important factors influencing the level of transport accessibility in the city. The higher the density of the route network, the smaller the number of transfers, but an increase in the number of routes requires an increase in the number of vehicles and, accordingly, large capital investments, which may be impractical with small passenger flows. If the number of vehicles is not increased, the traffic interval will increase, which will cause an increase in the time of waiting at stops. In such cases, the organization of transfers allows meeting the needs of trips while simultaneously taking into account the capabilities of transport service providers. Minimizing the waiting time for a transfer by synchronizing the operation of public transport and monitoring its operation in real-time makes it possible to achieve the appropriate level of passenger service quality [3].

3. RELEVANCE OF THE STUDY

In conditions of using the single fare system, the cost of the trip does not depend on the distance of transportation, payment is made separately for each boarding of the passenger. With such a system, the user of transport services often perceives a transfer negatively, even if it reduces the distance or duration of the trip because it increases the cost of the trip. The introduction of a system of electronic tickets with special tariffs for transfers (possibility of use on several routes or modes of transport during a certain period of time) will allow significantly reduce the impact of the cost factor on passengers' perception of transfers. With such a fare payment system, the duration of the trip becomes a determining factor. Modeling the probability of a transfer at a stop depending on the parameters of its operation based on the criterion of minimizing the passenger's time will allow assessing the actual demand for transport services between individual transport areas and determining the stops that play the role of crucial transport and transfer nodes of the route network.

4. FORMULATION OF THE AIM AND ARTICLE TASKS

The aim of the study is to estimate the probability of making a transfer at a stop of public passenger transport, taking into account the parameters of the stop's functioning based on the Bayesian approach. In connection with the set goal, the following tasks are defined:

- to carry out theoretical research on the application of Bayesian modeling to estimate the probability of a transfer at a bus stop;
- to conduct a study of influencing factors on the probability of transfer at a stop;
- to form a model of the route network of Lviv and to determine the parameters of passenger flows modeling at the stop;

- to simulate the probability of a transfer at the stops of the Lviv public transport;
- to evaluate the adequacy of modeling.

5. ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Optimizing the waiting time for transfers and their convenience for passengers is one of the important components of improving the quality of transportation by public transport. The presence of a transfer can be negatively perceived by the user of transport services when planning a trip. Often, the reason for such a lack of acceptance is the increase in the duration or cost of the trip and the increase in transport fatigue. When forming the utility functions of the trip, the parameter "transfer" usually has a negative coefficient [4].

In the article [5], the authors, based on their analysis, single out the following main parameters of transfers that affect their perception by passengers:

- availability and completeness of information about transfers (routes, schedules, interactive boards at bus stops with information on vehicle arrivals in real-time);
- safety (poor lighting at a stop or a dangerous (in the passenger's opinion) zone in which it is located significantly reduces the likelihood of using such a stop as a transfer hub);
- uncertainty (the user of transport services must be sufficiently sure that he will arrive at the destination in time);
- frequency (the frequency of vehicle movement on routes is a determining factor influencing the duration of waiting for a transfer);
- reliability (accurate adherence to schedules);
- arrangement of the stop (availability of rain protection, seats, escalators);
- method of transfer (at the disembarkation stop or with a transfer to another stop, availability of integrated ticketing systems);
- the availability of accessible seats (or the level of occupancy of the vehicle to which the transfer is made).

Other researchers distinguish three groups of factors that influence the passenger's desire to make a transfer: political, psychological, and operational [6].

The least studied are the political factors that characterize the influence of the activities of government or authorities regarding the formation and development of integrated transport systems on the encouragement of passengers to use transfers.

Psychological factors directly depend on the personal characteristics of the user of transport services: age, gender, presence of children or luggage, the purpose of the trip, familiarity with the station [7, 8].

The operational factors that affect the perception of the transfer by passengers include [9, 10]:

- trip duration;
- period of travel;
- the combination of modes of the trip (bus-bus, bus-railway);
- walking distance when transferring;
- waiting time for transfer;
- conditions for carrying out a transfer.

These components must be considered comprehensively, even though the station and interior design, the compilation of a route network and schedules, or the formation of a service system for passengers waiting for a transfer, usually differ in terms of the investment scale and responsible executors of these decisions. Lack of control or problems in dispatch management can lead to too short or too long transfer waiting. Each of these cases is negatively perceived by passengers [11–13].

In [3], the authors propose a methodology for determining significant transfer hubs for the route network using network topology indicators. However, the proposed method requires a matrix of data on passengers' transfers obtained from their smart cards, which are unavailable for Ukrainian conditions.

Simulations conducted using cumulative prospect theory and fuzzy logic revealed the influence between the predictability of the waiting time for a transfer and its perception by passengers [14]. For transfers up to 5 min, the exact waiting time was not particularly important, but for longer transfers, a significant correlation was observed between the passenger's awareness of the exact waiting time and positive perception of the transfer.

In [15], the author models the possibility of transferring at a urban public transport stop where two routes cross, by comparing the average and maximum values of the passenger's volume from the stop. The possibility of transfer is determined by the following conditions:

– the average number of passengers from the stop is less than the maximum number of passengers;
– the average number of arrivals at the stop is less than the maximum number of arrivals.

The authors' research [16] concerns transfers from different types of public transport (bus, tram, metro) to a train, as well as between trains. The utility function of the trip was transformed into the travel time and the relationship between the total value of utility and the transfer waiting time was determined. In general, the optimal transfer time is 8 minutes, and both shorter and longer durations reduce the utility of the transfer. There are also certain differences between travelers of different groups.

In the study [17], the authors focus on analysing the influence of the conditions of the transfer on its perception by passengers and, therefore, on the attractiveness of public transport. Modeling based on the public transport network of the Greater Copenhagen Region shows that transfer attributes such as ease of navigation and availability of shops can significantly change the attractiveness of a particular route: transfer penalty range from 5.4 min compared to bus in-vehicle time to 12.1 min.

6. PRESENTATION OF BASIC MATERIAL

Modeling the probability of a passenger changing at an urban public transport stop is one of the problems that can be solved using a Bayesian approach.

When setting up Bayesian networks, there is a need to configure the types of variables included in the network. If the network consists only of discrete variables, it is called discrete, if it consists of continuous variables, it is called continuous, and if both types of variables are combined in one network, it is called hybrid.

Hybrid Bayesian networks have certain limitations [18]:

– discrete variables cannot depend on continuous variables;
– continuous variables should be distributed according to the normal distribution.

For continuous variables, mathematical expectations and variances, and for discrete variables, the probabilities of a certain situation (the sum of the probabilities must be equal to one) are determined.

To find the relationship between several independent variables and one dependent one, if it is known (or it can be assumed) that the errors of the existing model have a normal distribution, then Bayesian logistic regression is used. The result of applying logistic regression is the probability of occurrence of a certain event.

The need for a transfer arises in the case of a combination of two reasons:

– the need to make a trip between two transport zones;
– lack of a direct route of the public transport between these transport zones.

The number of needs for trip will depend on the number of residents in the departure zone, and the probability of not having a direct route will depend on the total number of routes departing from this transport zone. In order to form a mathematical model of the relationship between these factors, it is necessary to analyse the population density in the city and the structure of the route network of public transport.

Theoretically, a transfer is possible at any public transport stop, but in practice, the probability of a transfer increases significantly if a new route appears at the stop which was not at the previous stop on the passenger's path. Also, potentially significant factors that can affect the probability of a transfer are the total number of passengers who disembark at the stop during a unit of time and the presence of routes at the stop that are not included in the urban route network.

The scheme of the hybrid Bayesian network for assessing the probability of a transfer at a stop of the urban public transportation system can be presented in the form shown in Fig. 1.

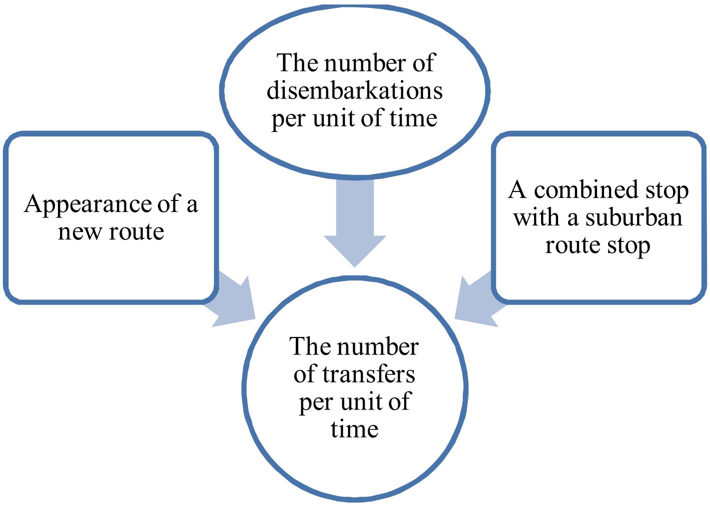

Fig. 1. Hybrid Bayes network (square vertices – discrete events, oval – continuous events)

Discrete vertices X_1 "appearance of a new route" and X_2 "availability of a suburban route at the stop" are characterized by two possible states each.

The continuous random variable Z_1 "the number of disembarkations per unit of time" has a continuous normal distribution with mathematical expectation μ_z and variable σ_z.

Influence of the parameters X_1, X_2 and Z_1 on the resulting continuous random variable Y_1 "the number of transfers per unit of time" is estimated using weighting factors k_i.

The estimated characteristics of the resulting value Y_1 can be determined by formulas [18]:

$$\mu_y = \sum_{i=1}^{2} p_{x1i} \cdot \sum_{i=1}^{2} p_{x2i} (\mu_x + k_1 \cdot \mu_z), \tag{1}$$

$$\sigma_y = \sum_{i=1}^{2} p_{x1i} \cdot \sum_{i=1}^{2} p_{x2i} \left((\mu_x + k_1 \cdot \mu_z)^2 + \sigma_x + k_1^2 \cdot \sigma_z \right) - \mu_y. \tag{2}$$

The probability of occurrence of the "transfer0 event will be:

$$P(X \mid Y = y, Z = z) = N\left(\mu_x(\mu_y, \mu_z), \sqrt{\sigma_x(\sqrt{\sigma_y})} \right). \tag{3}$$

To determine the weighting factors, there is need to have a large sample of data. The possibility of field or questionnaire surveys to collect the necessary information is complicated (in connection with the state of war and pandemic restrictions in Ukraine), therefore modeling with subsequent verification of the results at selected control points for adequacy can help to obtain a sufficient amount of information.

The software environment PTV Visum (Academic license) was used for modeling. The created model of the city of Lviv has 6.784 nodes (intersections), 16,618 road sections (links), 950 stops, 64 urban routes, and 14.224 trips/day according to schedules. The territory is divided into 950 transport zones. Information about the number of suburban routes that can stop there has also been added to the characteristics of the stops. The probability of having more than one route at a stop (based on the analysis of the route network) is 88 %, the probability of a new route appearing is 28 %, the probability of having a suburban route at the stop is 67 %.

A 4-stage transport demand model was used to forecast the volume of passenger traffic at each of the stops. The redistribution was carried out on the basis of intervals, the redistribution parameters are given in the Table 1.

In result of the modeling procedure, in particular, the daily values of the number of boarding, disembarkations, and transfers at each of the stops were obtained (transfers can take place either directly at the stop or by walking to an adjacent stop). In Fig. 2 shows the results of the simulation of the number of transfers: with a division into those transfers that are performed directly at the stop and transfers that are performed by walking to a nearby stop (within a radius of 200 m).

Table 1

Assignment procedure parameters

Assignment parameters	Calculation method	Formula apparatus
Method of headway calculating	From mean waiting time $\tau^{a,b}$ according to timetable	$\tau^{a,b} = \frac{1}{b-a}\sum_{i=0}^{n}\Delta_i$ $\Delta_0 = (x_1 - a)^2$ $\Delta_i = (x_{i+1} - x_i)^2$ $\Delta_n = (x_{n+1} - x_n)^2 - (x_{n+1} - b)^2$ Where: a,b – the time interval for which the average waiting time is determined; n – the number of trips in the time interval $[a,b]$; Δ_i – the time interval between two step-by-step departures; x_i – time of departure i.
Impedance function *IMP*	–	$IMP = PJT \cdot k_1 + NFP \cdot k_2$ Where: PJT – perceived journey time; NFP – trip cost; k_1, k_2 – the coefficients of the influence of the perceived journey time and the cost of the trip on impedance to transportation.
Perceived journey time PJT	–	$PJT = T_{iv} + T_a + T_e + T_{tr.walk} \cdot k_1 + T_{owalk} + T_{tr.wait} + k_2 \cdot N_{tr}$ Where: T_{iv} – in-vehicle time, min; T_a – access time; T_e – egress time; $T_{tr.walk}$ – transfer walk time; T_{owalk} – origin wait time; $T_{tr.wait}$ – transfer wait time; N_{tr} – number of transfers.
Passenger\`s route choice model	No information and constant headways	The probability of a passenger choosing a route from a set of possible ones: $\pi_i = \lambda_i \int_0^{\bar{h}} \prod (1 - \lambda_j \cdot w) dw$ $\bar{h} = \min\{h_i\}$ – minimal occurring headway; λ_i – frequency of route i; w – waiting time, min.

The resulting linear regression model of the number of transfers per day at a stop (multiple correlation coefficient is R = 0.78) has a form:

$$N_{transfer} = -0.77 \cdot N_{suburban} + 5.24 \cdot N_{urban} + 0.85 N_{dis} - 51.9, \tag{4}$$

where $N_{suburban}$ – the number of non-urban routes stopping at the stop; N_{urban} – the number of urban routes stopping at the stop; N_{dis} – total number of passengers disembarking at this stop (pass/day).

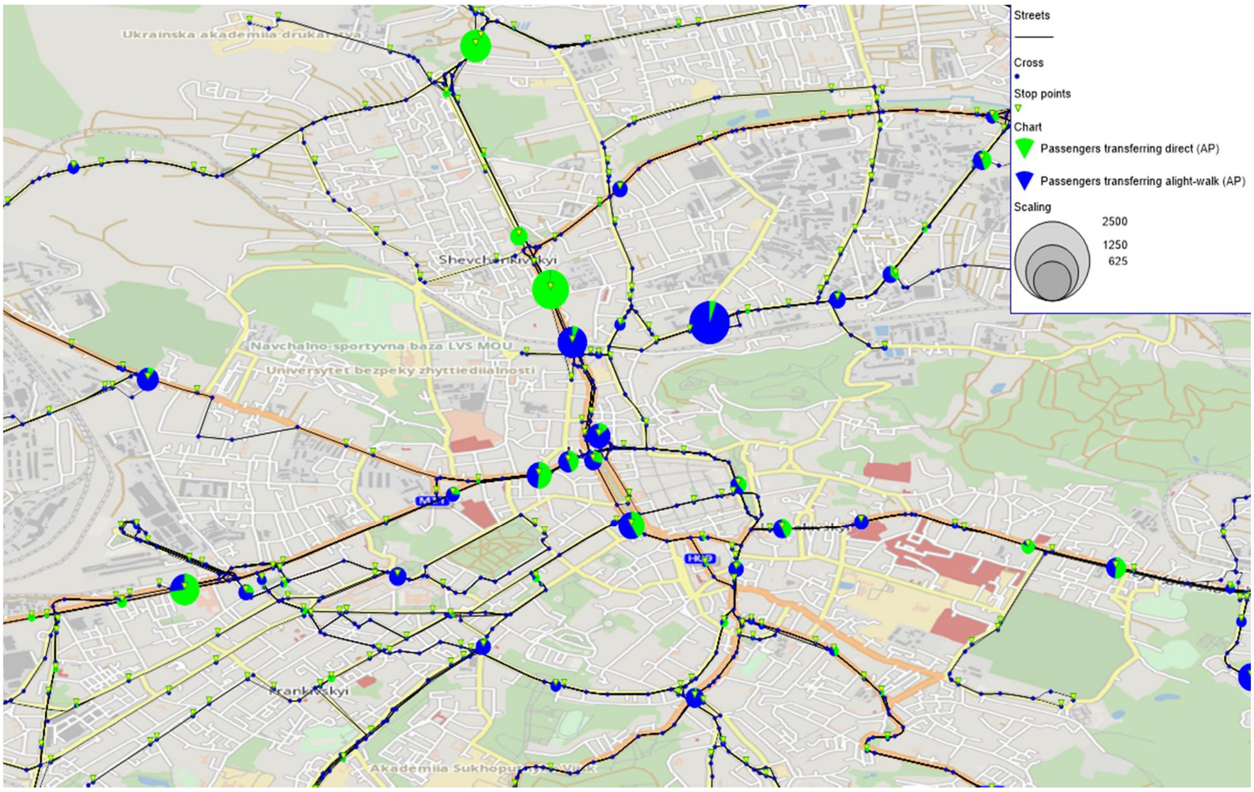

Fig. 2. Diagram of the number of transfers at the stops of the Lviv public transport network (fragment) – simulation results in the PTV Visum software environment

The results of modeling the average duration of waiting for a transfer in the case of uniform operation of vehicles on the routes (strict adherence to schedules) are presented in Fig. 3, and in the case of possible fluctuations within the schedule – in Fig. 4.

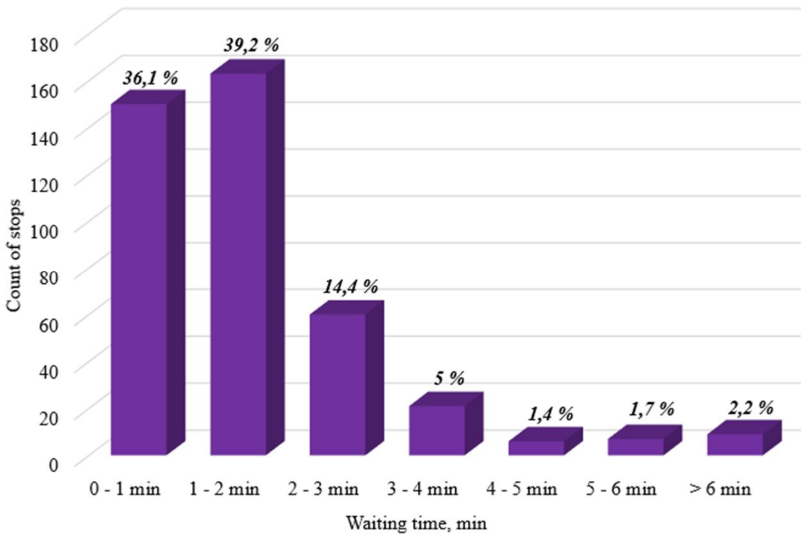

Fig. 3. Modeling the average waiting time for a transfer at a stop (rhythmical arrival of vehicles)

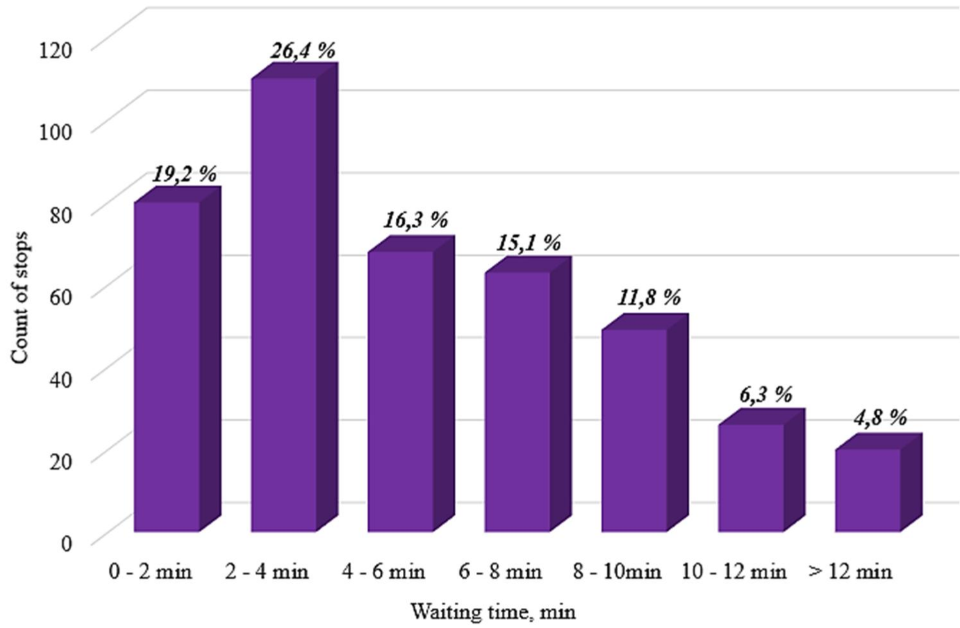

Fig. 4. Modeling the average waiting time for a transfer at a stop (fluctuations arrival of vehicles)

With strict adherence to the traffic schedule, the average waiting time does not exceed 3 minutes in 90 % of cases, and only in 2.2 % is it more than 6 minutes. In the case of irregular arrivals, the average waiting time fluctuates more: the waiting time does not exceed 4 minutes in 46 % of cases, in 16 % of cases it is within 4-6 minutes, and in 38 % of cases it is more than 6 minutes (of which 11 % – more than 10 minutes).

To check the adequacy of modeling results and the feasibility of using a Bayesian approach to assessing the probability of a transfer, a comparison of the calculation results and simulation results was made for the “Magnus” stop, which is located in the central part of the Lviv and is characterized by significant passenger traffic during the day. Public transport routes arrive at the stop from two directions: direction I – Horodotska Str. and direction II – Chornovola Ave. suburban buses also arrive at the stop from direction II. The characteristics of the operation of the stop, obtained as a result of field (autumn 2021) and documental studies and calculations based on them, are presented in the Table. 2.

Table 2

Characteristics of the operation of the “Magnus” stop

Indicator	Indicator value
The total number of urban routes passing through the stop	14
Average headway on urban routes, min	15
The total number of suburban routes passing through the stop	6
Average headway on suburban routes, min	20
Number of new urban routes (compared to those at the previous stop)	5/9
The probability of the appearance of a new urban route for passengers from the direction I	0.36
The probability of the appearance of a new urban route for passengers from the direction II	0.64
Mathematical expectation of the number of passengers disembarking at the stop, μ_{dis}, pass/day	6125
Dispersion of the number of passengers disembarking at the stop, σ_{dis}, pass/day	612

The probability of a transfer at a stop calculated by the formula (3) based on these data is 16.4 %. The characteristics of the transfer at this stop, obtained as a result of simulation, are presented in Fig. 5.

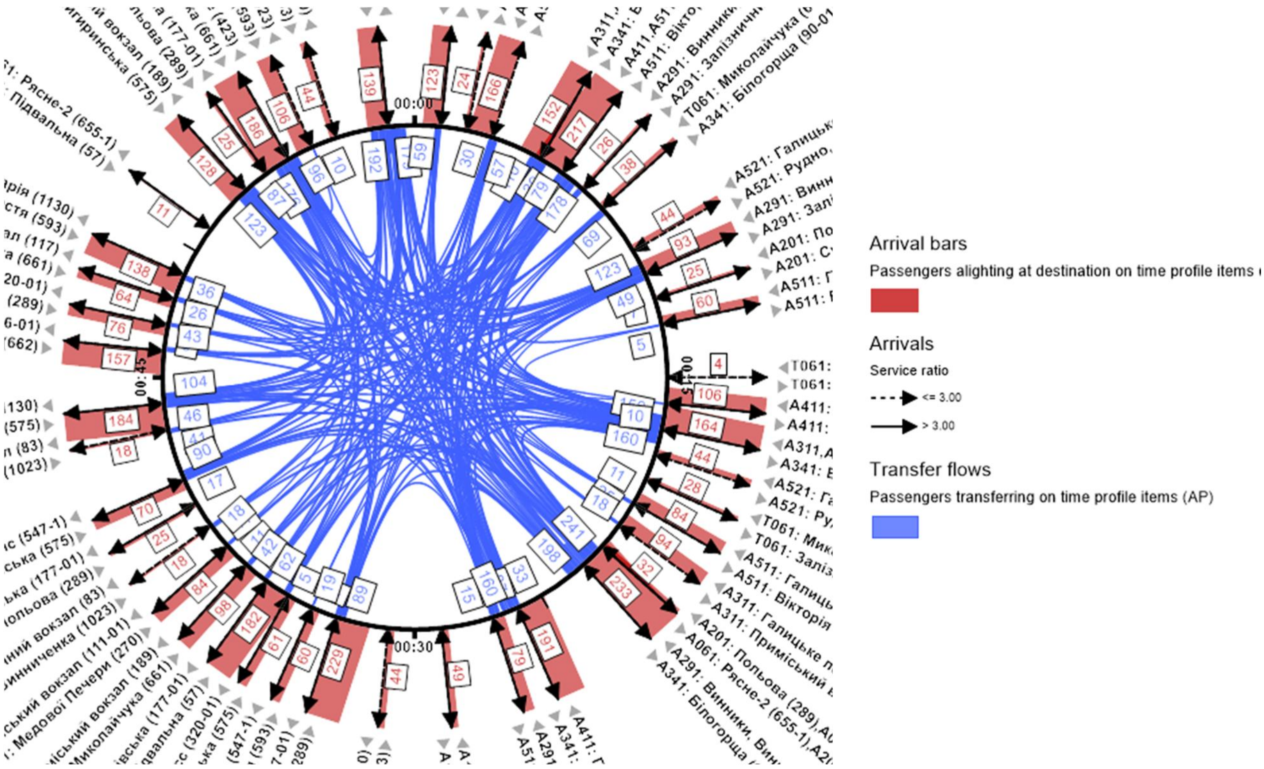

Fig. 5. Results of simulation of transfers at the "Magnus" stop in the PTV Visum software environment

The simulated probability of a transfer at a stop is 12 %.

7. CONCLUSIONS AND FUTURE RESEARCH PERSPECTIVES

As results of this research, such conclusions can be made:

1. When forecasting the demand for transportation in the urban transport system, one of the problems is taking into account the probability of a passenger transfers at a stop. The user's perception of transfer transport services is influenced by various factors: his personal characteristics and the parameters of the route network, and indicators of the operation of stops. Bayesian networks as a form of representation of a system of probabilistic processes in the form of a graph, where vertex represent random variables (which can be both discrete and continuous), and edges represent the presence of the influence of one variable on another, are one of the effective methods of searching for cause-and-effect relationships between different types of input and output parameters.
2. To estimate the probability of a transfer at a public transport stop using the Bayesian approach, the input parameters are the number of disembarkations at the stop per unit of time and the probability of a new route of the urban route network appearing at the stop, which was not present at the previous stop on the way of the passenger, or suburban route, which can board passengers at this stop.
3. In result of modeling, conducted in the PTV Visum software environment for the route network of Lviv city, data were obtained on passenger flow at public transport stops with distribution by numbers of passengers who: disembark at the stop (73 %); make a transfer at the disembarkation stop (11 %); walking to another stop to make a transfer (16 %).
4. The average waiting time for a transfer at a stop depends on both the number of routes passing through the stop and their regularity. With strict adherence to the schedule, in 90 % of cases the average waiting time does not exceed 3 minutes, and only in 2.2 % it is more than 6 minutes. In the case of irregular arrivals, the average waiting time fluctuates more: in 46 % of cases, the

waiting time does not exceed 4 minutes, in 16 % of cases it is within 4-6 minutes, and in 38% of cases it is more than 6 minutes (of which 11 % – more than 10 minutes).

5. A comparison of the results of calculating the probability of a transfer at one of the basic stops was carried out to check the adequacy of the modeling. The calculated probability is 0.16, the simulated probability is 0.12.
6. Determining the probability of a transfer in the route network using Bayesian networks makes it possible to optimize the timetables of public transport routes, in particular, those that move in certain directions.

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ЗАСТОСУВАННЯ БАЙЄСІВСЬКИХ МЕРЕЖ ДЛЯ ОЦІНКИ ЙМОВІРНОСТІ ПЕРЕСАДКИ НА ЗУПИНЦІ ГРОМАДСЬКОГО ТРАНСПОРТУ

Анотація. *Оптимізація пересадок при функціонуванні громадського транспорту є одним з важливих компонентів підвищення якості перевезень. На сприйняття пересадки пасажиром впливає ряд чинників: від особистісних характеристик користувача транспортних послуг до параметрів маршрутної мережі, характеристик поїздки та дизайну пересадкових зупинок. Для пошуку взаємозв'язку між різними типами вхідних даних, які впливають на ймовірність виконання пересадки на зупинці, використано метод побудови Байєсівських мереж як один з ефективних методів розв'язання задач прогнозування складних систем.*

Потреба в пересадці виникає в пасажира при поєднанні двох причин: потреби у виконанні поїздки між двома транспортними районами та відсутності прямого маршруту громадського транспорту між цими транспортними районами. Кількість потреб у виконанні поїздки залежатиме від кількості жителів в районі відправки, а ймовірність відсутності прямого маршруту – від загальної кількості маршрутів, які відправляються з цього району. Для визначення впливу цих чинників на ймовірність пересадки на зупинці проведено моделювання у програмному середовищі PTV Visum (на прикладі м. Львова). В результаті отримано дані щодо загальної величини пасажирообміну на зупинках ГПТ з розподілом на кількість пасажирів, які здійснюють висадку на зупинці, кількість пасажирів, які здійснюють пересадку на цій зупинці та кількість пасажирів, які здійснюють перехід (до 200 м) на іншу зупинку для виконання пересадки. Середня тривалість очікування пересадки на зупинці залежить як від кількості маршрутів, що проходять через зупинку, так і від регулярності руху. Чітке дотримання розкладів руху сприяє зменшенню середньої тривалості очікування пересадки. Для перевірки адекватності моделювання проведено порівняння результатів розрахунку ймовірності пересадки на одній із зупинок з використанням розрахунків на основі даних натурних спостережень та з використанням моделювання. Розрахована ймовірність становить 0,16, змодельована – 0,12.

Ключові слова: *маршрутна мережа, байєсівська мережа, моделювання транспорту, ймовірність пересадки на зупинці, PTV Visum.*